Improving the impact toughness of the Hy-Tuf steel by austempering

Cite as: AIP Conference Proceedings **2053**, 040054 (2018); https://doi.org/10.1063/1.5084492
Published Online: 19 December 2018

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Improving the Impact Toughness of the Hy-Tuf Steel by Austempering

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Abstract. The microstructure and mechanical properties of the high-strength Hy-Tuf steel are studied after different heat treatment modes – conventional oil quenching and tempering, austempering in the bainite transformation temperature range. It is shown that the tempering embrittlement of the Hy-Tuf steel can be observed at temperatures ranging between 400 and 500 °C. The highest impact toughness of the studied steel for the case of conventional oil quenching and tempering (1.2 MJ/m^2) can be achieved after high temperature tempering (600 °C), which also leads to the deterioration of tensile strength down to 800…900 MPa. The unique combination of high tensile strength (above 1300 MPa), elongation (up to 15%) and impact toughness (1.1 MJ/m^2) is obtained after austempering at a low transformation temperature.

INTRODUCTION

One of the most important matters of the engineering science nowadays is to improve reliability and to reduce the weight of the parts at the same time [1–3]. Therefore, the material of such parts should possess both high strength and high toughness. Many scientific studies have been conducted to meet this requirement using steels as the most widely applied metallic alloys [4, 5]. As a result of such studies, new steel types were discovered, namely, TRIP (transformation-induced plasticity) steels [6–8], TWIP (twinning-induced plasticity) steels [9–11], QP (quenching-partitioning) steels [12–15], etc. The main disadvantage of TRIP and TWIP steels is their high cost due to a high content of alloying elements. QP steels intensively studied for the last 10 to 15 years were designed mainly to be applied in the car industry for thin-walled or sheet parts [16, 17]. The optimal steel for massive engineering parts should contain less than 8 wt% of alloying elements, have sufficient hardenability and provide high strength and plasticity. The high-strength Hy-Tuf steel meets these requirements. This steel is usually used for the production of aircraft parts, mining equipment and other high-performance products [18, 19]. In most cases, the final mechanical properties of the Hy-Tuf steel parts are obtained by conventional quenching and tempering. The present study is aimed to investigate the possibility of improving the strength-toughness combination of the Hy-Tuf steel.

EXPERIMENTAL

The chemical composition of the Hy-Tuf steel is presented in Table 1. The steel was produced using a commercial electric arc furnace. The heat volume was 30 tons. The steel was cast into ingots, then homogenized at 1200 °C for 12 h, hot rolled into a bar with a diameter of 140 mm and annealed. The initial microstructure of the steel under study was a ferrite matrix with uniformly distributed globular carbide particles.

The temperatures $Ac_1 = 730$ °C and $Ac_3 = 875$ °C were determined from dilatometric experiments [20]. The heating temperature was set 925 °C (40 min) to provide more complete dissolution of the carbide particles. The steel specimens were quenched in industrial oil (40 to 60 °C) and then tempered for 3 h at temperatures ranging from 200 to 600 °C.

Mechanics, Resource and Diagnostics of Materials and Structures (MRDMS-2018)
AIP Conf. Proc. 2053, 040054-1–040054-4; https://doi.org/10.1063/1.5084492
Published by AIP Publishing. 978-0-7354-1781-6/$30.00

TABLE 1. The chemical composition of the Hy-Tuf steel, wt%

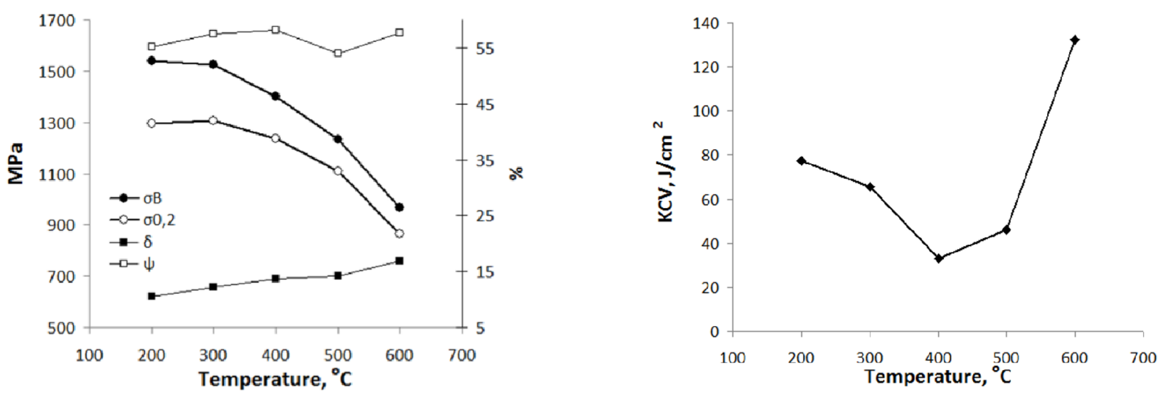
C	Si	Mn	Cr	Ni	Mo	Cu	S	P
0.24	1.42	1.35	0.31	1.71	0.40	0.16	0.004	0.008

The austempering of the Hy-Tuf steel was conducted with the use of a salt bath (50% KNO_3, 50% $NaNO_3$). The temperature of isothermal holding was 330 to 430 °C and the holding time was 60 min. After austempering, the specimens were quenched in industrial oil.

The mechanical properties were determined according to the standard practice (ASTM E8) using the type 3 specimens. The Charpy impact tests were conducted according to ASTM E23 at room temperature. The hardness of the steel was measured according to ASTM E18 (Rockwell hardness) and ASTM E92 (Vickers hardness). The microstructure of the steel was analyzed by a Meiji IM-7200 light microscope. The retained austenite volume fraction was determined by X-ray analysis using a Bruker D8 Advance diffractometer.

RESULTS AND DISCUSSION

The mechanical properties of the Hy-Tuf steel after oil quenching and tempering at temperatures ranging between 200 and 600 °C are presented in Fig. 1. Tempering embrittlement was observed at 400 °C. Impact toughness at this tempering temperature dropped down to 30…35 J/cm^2. The increase of the temperature to 600 °C provided a sufficient increase in impact toughness to 130…140 J/cm^2, but the tensile strength of the steel decreased to 960 MPa.



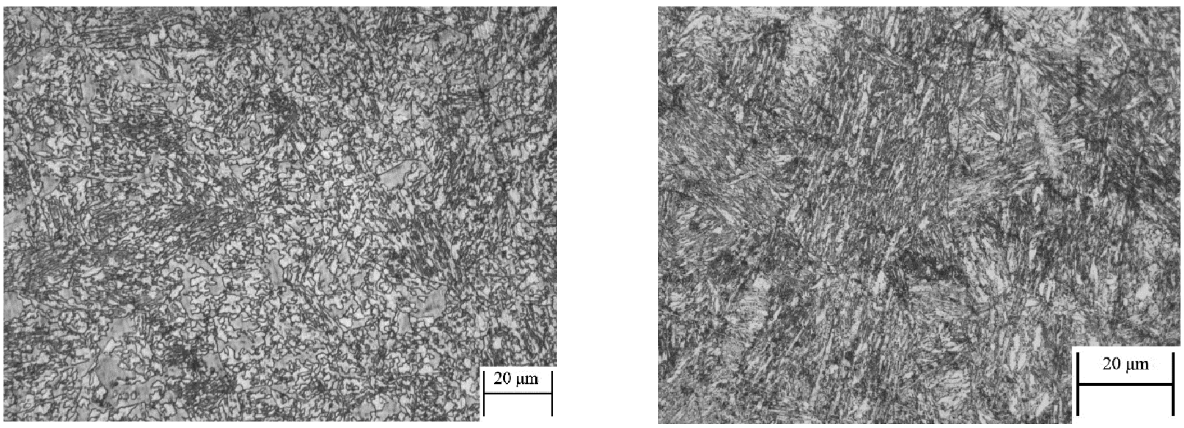
(a) (b)

FIGURE 1. The mechanical properties of the Hy-Tuf steel after quenching (925 °C, 40 min, oil) and tempering (3 h): a) tensile test; b) Charpy impact test

The austempering of the steel was carried out at temperatures of 330, 370, 400 and 430 °C. The microstructure of the Hy-Tuf steel austempered at 400 and 430 °C contained upper bainite and martensite formed during final oil cooling (Fig. 2a). The decrease of the austempering temperature to 370 °C led to the shift of the bainite morphology to lower bainite. The microstructure obtained after austempering below the M_s temperature at 330 °C (Fig. 2b) contains laths of "primary" martensite (formed during cooling down to the austempering temperature) and lower bainite. X-ray diffraction showed the presence of 12 to 18% of retained austenite in the Hy-Tuf steel microstructure after austempering.

The impact toughness of upper bainite formed at temperatures ranging between 400 and 430 °C was found to be very low (15 to 20 J/cm^2) despite the sufficient amount of retained austenite (up to 15…18%). The main reason for the observed phenomena is carbide precipitation from retained austenite during the isothermal holding leading to a decrease in the carbon content in the retained austenite. The lower the carbon concentration, the lower the stability of the retained austenite, and fresh brittle martensite would form at lower applied stresses. Thus, both carbides and insufficient austenite stability are the main reasons for the low impact toughness of the Hy-Tuf steel austempered at the temperatures of upper bainite formation above 400 °C.

The decrease of the isothermal transformation temperature down to 370 °C provided sufficiently higher impact toughness (75 J/cm^2) due to the formation of lower bainite; however, the tensile strength decreased from 1300…1400 MPa (at temperatures of 400 to 430 °C) to 1180 MPa. The decrease of the tensile strength was due to more complete bainite transformation at a temperature of 370 °C and, as a result, a smaller amount of martensite in the steel microstructure. A further decrease in the austempering temperature to below M_s (to 330 °C) provided the best combination of high impact toughness (110 to 115 J/cm^2) and high tensile strength (1320 to 1330 MPa). The increase of the impact toughness is attributed to the absence of carbides or upper bainite in the final microstructure and high stability of the carbon-enriched austenite. The increased tensile strength is due to the formation of some amount of the "primary" martensite and to the TRIP effect of the retained austenite to martensite transformation during the plastic deformation.



(a) (b)

FIGURE 2. The microstructure of the Hy-Tuf steel after austempering at temperatures of 430 °C (a) and 330 °C (b)

The obtained mechanical properties of the Hy-Tuf steel after low-temperature austempering below M_s combine high ductility and impact toughness (typical of high-temperature tempering conditions of the oil-quenched steel), and a high strength level, which allows one to reduce the dimensions of steel parts to provide specific strength.

CONCLUSION

1. The mechanical properties of the Hy-Tuf steel after oil quenching and tempering at temperatures ranging between 200 and 600 °C have been analyzed. Tensile strength decreases from 1540 MPa to 960 MPa, elongation increased from 10 to 17%, and the reduction of area was almost constant (54 to 57%) in the studied tempering temperature range.
2. Tempering embrittlement is observed at 400 °C for the steel under study (the Charpy impact toughness is 30 to 35 J/cm^2). The increase of the tempering temperature to 600 °C provides an increase in the impact toughness to between 130 and 140 J/cm^2.
3. Austempering of the Hy-Tuf steel at 400 to 430 °C provides the formation of upper bainite possessing very low impact toughness (15 to 20 J/cm^2) due to carbide precipitation and low stability of the retained austenite.
4. Austempering at 330 °C (below the M_s temperature) forms a complex microstructure consisting of "primary" martensite, lower bainite and carbon-enriched retained austenite. The impact toughness increases to between 110 and 115 J/cm^2 providing the best combination of high impact toughness and high tensile strength (1320 to 1330 MPa).

ACKNOWLEDGMENTS

The work was performed within the framework of the Grant from the Russian Federation President for young scientists Ph.D. MK-7929.2016.8 and supported by the Russian Federation Ministry of Education and Science (project No. 11.1465.2014/K) and the Russian Federation Government (Act No. 211, contract No. 02.A03.21.0006).

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